POSSIBLE MECHANISMS FOR ELECTRIC-FIELD-FREE GAS BREAKDOWN

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Abstract

It was reported in the late 1960s [1] that gas breakdown occurs during explosive and electrical operation of magnetic flux compressor generators (FCGs). Recently [2,3], we reported on experimental evidence of the formation of plasma and its propagation in the gas within the FCG with no electric field in the system. We named this phenomenon electric-field-free gas breakdown. In this paper, we discuss possible mechanisms for this type of gas breakdown. The first mechanism is related to the ionization of the gas by a sequence of shock processes caused by an explosively expanding metallic armature within an FCG. The second mechanism is related to the ejection of high-speed particles from the explosively shocked metallic surface of an FCG armature.

I. INTRODUCTION AND BACKGROUND

Initiation of gas discharges in helical magnetic flux compression generators was reported in the 1960s [1]. It was shown in [4,5] that the gas discharge is not itself a source of magnetic flux loss in the FCG; however, high current densities created by the discharge in the armature and the stator of the FCG increase the rate of flux diffusion into the conductors that causes flux loss in the generator. It was demonstrated that flux loss in FCGs increases about 50% due to this discharge.

In order to obtain detailed information about the initiation and development of gas discharges during different stages of FCG operation we performed experimental studies using high-speed photography to record processes that occur within the generators [2,3]. We conducted two types of experiments. The experiments of the first type [2] were performed with explosively expanded FCG copper armatures with no magnetic and electric fields in the system. The experiments of the second type [3] were performed by simultaneously recording electric signals produced by a loop magnetic flux compression generator (LFCG) [6] and high-speed photography of its explosive operation.

In this paper we present high-speed images of gas breakdown within the FCGs and discuss possible mechanisms of plasma initiation.

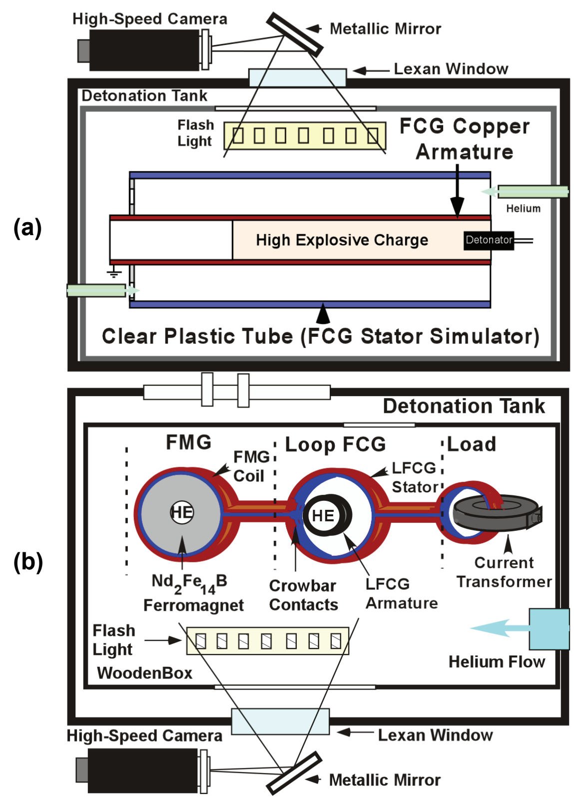

Figure 1. Schematic diagrams of explosive experiments (a) with a copper FCG armature and (b) with the LFCG.

II. EXPERIMENTAL RESULTS

Schematic diagrams of the experimental setups are in Fig. 1. The experiments were conducted in the facilities of the Energetic Materials Research Laboratory at the

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14. ABSTRACT

It was reported in the late 1960s [1] that gas breakdown occurs during explosive and electrical operation of magnetic flux compressor generators (FCGs). Recently [2,3], we reported on experimental evidence of the formation of plasma and its propagation in the gas within the FCG with no electric field in the system. We named this phenomenon electric-field-free gas breakdown. In this paper, we discuss possible mechanisms for this type of gas breakdown. The first mechanism is related to the ionization of the gas by a sequence of shock processes caused by an explosively expanding metallic armature within an FCG. The second mechanism is related to the ejection of high-speed particles from the explosively shocked metallic surface of an FCG armature.

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Missouri University of Science and Technology, Rolla, MO. Camera synchronization and other technical details are given in [2, 3].

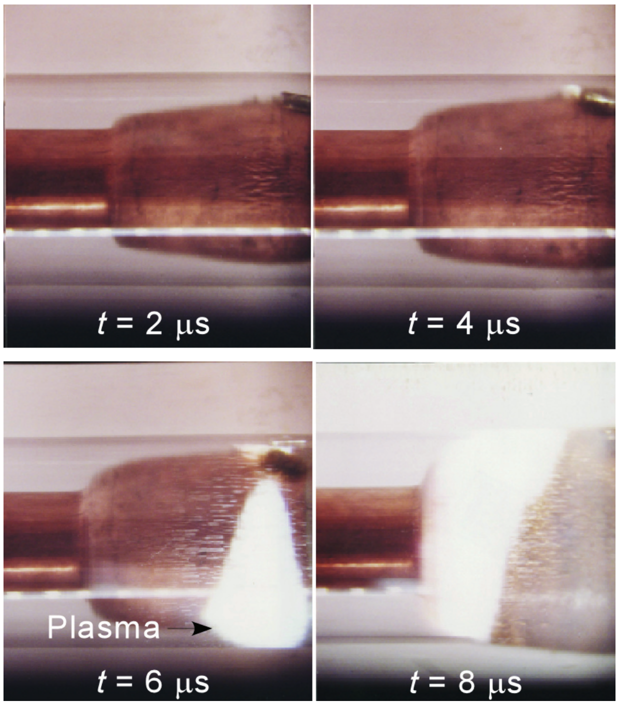

Figure 2. Series of high-speed photographs taken during explosive expansion of the FCG copper armature.

In the first series of experiments, performed as a portion of AFOSR's MURI 98 grant, an FCG armature was explosively expanded without any electric and magnetic field in the system [Fig. 1(a)]. We loaded the oxygen-free high-conductivity cylindrical copper armature (outer diameter, o.d.=50.8 mm, inner diameter, i.d.=46.2 mm, and length, h=170 mm) at one end with a 225 g cylindrical explosive charge of desensitized RDX explosive (Chapman–Jouguet state pressure of 22.4 GPa), and we initiated the explosive charge using a single RP-501 detonator. The armature was placed inside a clear polycarbonate tube (o.d. = 82.7 mm, i.d. = 77.0 mm, and h = 150 mm) that served as a substitute of the stator of the FCG. There were no electric potentials, electric currents, or electric and magnetic fields in the system. We ignored the presence of Earth's magnetic field in these experiments due to the field's negligibly low intensity in comparison with typical values of magnetic flux density in actual FCGs [7, 8]. The clear plastic tube made it possible to observe, in detail, the processes occurring during explosive expansion of the armature. The tube confined the gas between the explosively expanding armature and the inner wall of the tube, in the same way that the expanding armature and stationary stator of an actual helical FCG traps gas. In addition, the tube simulated the wire insulation of the coil forming the stator of a helical FCG.

The operation of the system [Fig. 1(a)] started with the point detonation of its HE charge at the end of the copper armature. The expanding detonation shock within the explosive charge reached the inner wall of the armature, went through the armature thickness as an overdriven acoustic shock, and emerged from the armature outer surface. Because of this action, the armature started its expansion. The radial velocity of expansion of the armature as determined by measurements from the high-speed photographs was 3.0±0.1 km/s. When the explosively expanding armature approached the inner wall of the plastic tube, an intense plasma formed around the expanding armature (Fig. 2). This phenomenon documented by these photographs is direct experimental evidence of the formation of plasma and the propagation of the plasma front in the FCG purely due to the explosive motion of conductors; there were no electric or magnetic fields in the system. This means that in actual explosively driven generators the gas breakdown does not depend on the electric field strength in the system. Therefore, even with no electric field in the system, it is possible to form plasma in the FCG.

Figure 3. High-speed photographs taken during explosive and electrical operation of the LFCG.

The second series of experiments was performed with the loop FCGs [schematic diagram of the experimental setup is in Fig. 1(b)]. The explosive and electrical operation of an LFCG is similar to that of other types of FCGs based on magnetic flux compression inside the stator due to the explosively driven expansion of a cylindrical armature. The specific feature of an LFCG that made it useful for these experiments is the opportunity to observe in detail the processes that occur inside the generator (expansion of the armature, closing the crowbar contacts, etc.) from the very beginning until the final stage of its operation.

An external seed source generated the initial current of 2.6 kA before explosive operation of the LFCG. The two detonators of the LFCG were initiated at t=26 μs, and one can see the light coming from the detonation of the HE inside an armature of the LFCG [Fig. 3(t=26 μs)]. As the LFCG armature started its expansion [Fig. 3(t=30 μs)], gas breakdown occurred within the LFCG and plasma appeared in the gap between the armature and the crowbar. The electric field strength between the armature and the crowbar contacts was negligible during operation of the system; it did not exceed 7 V/mm. This electric field was not high enough to initiate gas breakdown and form plasma. Further expansion of the armature [Fig. 3 (t=30 μs, 32 μs, 38 μs)] was accompanied by the generation of an intense plasma that filled the gap between the armature and the stator. The plasma front propagated along the inner perimeter of the stator. This is additional experimental evidence of the formation of plasmas in explosive electric generators, in the absence of external electric fields or at low electric field, by explosively driven metallic elements.

III. BREAKDOWN MECHANISMS

It follows from the experimental results described above that the formation of plasma and the propagation of the plasma front occur in the FCGs with no electric field. Electric-field-free gas breakdown can cause the development of intense electric discharges in gas within the generators, even in the presence of low intensity electric fields. The electrical insulation of the FCG winding would limit electrical contact between the initial plasma and the FCG stator, and correspondingly would avoid the development of plasmas. Nevertheless, it has been reported [4,5] that even heavy insulation of windings of FCG stators does not help to solve this problem.

A. Repeated Shocks from Explosively Expanding Armature

The electric-field-free gas breakdown within the stator of the FCG is probably the result of two different shock processes in the gas between the stator of the FCG and the expanding armature. The first shock process results from the detonation of the HE inside the armature. Passage of this detonation shock through the FCG compresses, heats and excites the gas within the flux compressor.

After the detonation shock front propagates through the gas, the armature begins its expansion (see timing above). Based on high-speed photographic images of the LFCG [Fig. 1(b) and Fig. 3], the speed of the expansion is 1.6±0.1 mm/μs during the initial stage of the expansion and 2.9±0.1 mm/μs during the final stage. The velocity of expansion of the armature of a helical FCG (Fig. 2) was 3.0±0.1 km/s. This is nearly three times faster than the normal acoustic velocity of the gas fill; therefore, a shock wave is formed in the gas in the path of this expansion. This second shock builds in front of the expanding armature, re-compressing already shocked gas. The compression process results in greater heating, and therefore, greater excitation of the gas immediately in front of the expanding armature when compared to the excitation caused only by the passage of the detonation shock. Figure 4(a) illustrates this mechanism of gas ionization and gas breakdown in the case of the LFCG.

Because of these two shock processes occurring in quick succession, a part of the gas is ionized and plasma is formed in the gas between the armature and the stator. The appearance of this plasma and the propagation of the plasma front cause the initiation of the electric discharge in the system even at very low electric fields. It is obvious that the plasma formation processes observed and herein described takes place in loop, helical and coaxial FCGs, where cylindrically expanding armatures cause the formation of plasma and the initiation of the electrical discharges.

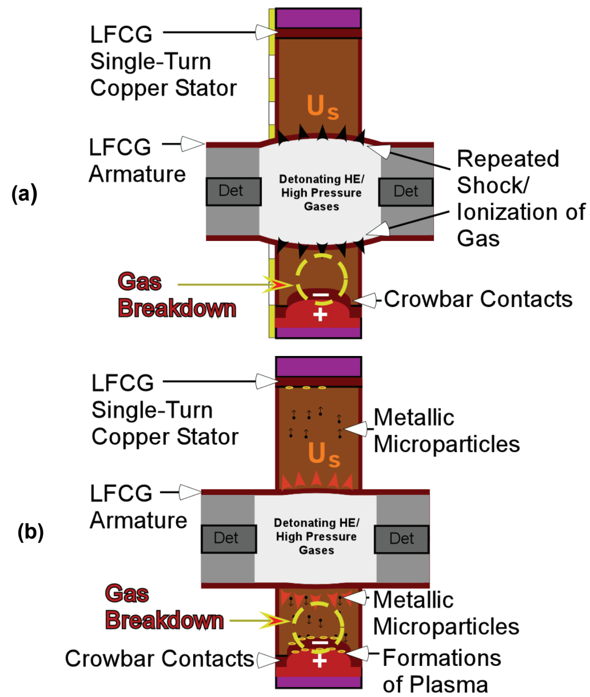

Figure 4. Schematic diagrams illustrating possible mechanisms for electric-field-free gas breakdown in the LFCG (see the text).

Because of the hydrodynamic performance of conducting and insulating materials under shock loading within the generator, there are no design-independent thresholds for the formation of plasma and initiation of discharge; the thresholds will depend on the shape and placement of the conductors and insulators, and on the materials used for each. Repeated shocking of the materials between the expanding armature and the stator makes it difficult to provide effective electrical insulation within the FCG from the beginning until the final stage of its explosive and electrical operation. Solving this problem will require the use of thin film insulators that cannot be ionized by multiple shocks. Whatever insulation coating is chosen for the armature, it would have to remain undamaged in order to continue as an insulator at the very high strain rates and high material elongations experienced by the explosively expanding armature, which is unlikely.

B. High Speed Particle Ejection from Explosively Expanding Armature Surface

Another possible mechanism for electric-field-free gas breakdown in the FCGs is related to recent findings on the ejection of particles from explosively shocked metallic surfaces [10-12]. It was experimentally demonstrated in [10-12] that the ejection of particles from a shocked metallic surface into an adjoining gas occurs when the shock pressure is greater than the shock-breakout pressure (P_{SB}) at the surface of the metal. The particle size varies from 20 to 200 μm. Based on the micro-images presented in [11], the density of the accelerated particles can be estimated as 10^4 particles/cm^2. Particle velocities range from 1.0 to 1.5 km/s [10-12]. The shock-breakdown pressure for tin is $P_{SB} \approx 27.5$ GPa [12]. The P_{SB} for aluminum is not known, but the theoretical pressure at the shock front in C-4 is $P_{SW} = 36.7$ GPa, which is well over the reported P_{SB} value for tin.

These experimental results enable us to propose a possible mechanism for electric-field-free gas breakdown within FCGs. A schematic diagram illustrating this mechanism in the case of the LFCG is in Fig. 4(b). LFCG operation starts with the detonation of its HE charge. The expanding detonation shock within the explosive charge reaches the inner wall of the armature, goes through the armature thickness, and emerges from the armature outer surface. As the shock front leaves the armature, it causes an ejection of high-speed metallic particles (which were detected and studied in [10-12]) toward the stator. A few microseconds later, the metallic particles reach the stator of the FCG and bombard the inner wall of the stator facing the armature [Fig. 4(b)]. This bombardment initiates plasma at the surface of the stator. If the winding of the stator is insulated, the bombardment destroys the insulation of the winding in addition to creating plasma. This plasma can then cause the development of an electric discharge in the area around the damaged electrical insulation of the winding in the presence of an electric field.

IV. SUMMARY

Based on observed experimental results, an electric field does not have to be present to initiate gas breakdown, which can, in turn, cause the development of intense gas discharges even when low electric fields are generated in a FCG armature-stator circuit. This breakdown is different from all known types of gas breakdown. This phenomenon is called electric-field-free gas breakdown. Two possible mechanisms for this phenomenon were proposed in this paper.

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